# Beyond cost and carbon: the multidimensional co-benefits of low carbon transitions in Europe

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## 1. Introduction

In this study, based on a mixed methods approach, we catalogue 128 prospective co-benefits to four European low carbon transitions. This includes 30 co-benefits for French nuclear power, 30 co-benefits for German solar photovoltaics (PV), 26 co-benefits for Norwegian electric vehicles (EVs), and 42 co-benefits for smart meters in Great Britain. Tellingly, 37 of these collective benefits are identified as economic and 14 environmental, but the remaining ones illustrate a broader spectrum of technical, social, and political benefits (77 in total).

The study is structured as follows. It firstly defines and conceptualizes the co-benefits to climate change mitigation and low carbon transitions. It then justifies the four case studies of France, Germany, Norway, and Great Britain, and explains its primary research methods of expert interviews, public focus groups, and the utilization of public internet forums. Then, it presents the 128 identified potential co-benefits. After presenting this body of evidence, the paper then discusses and theorizes these benefits more deeply in terms of complementarity, temporality, scale, actors, and incumbency. It concludes with more general insights for energy and climate research, and policy.

## 2. Defining co-benefits, case selection and research design

As a starting point, this section defines and conceptualizes co-benefits, justifies our four cases, introduces our mixed methods research design, and identifies limitations and shortcomings with our approach.

### *2.1 Defining and conceptualizing co-benefits*

Co-benefits, or "co-impacts" in the context of low carbon transitions, in the broadest and simplest sense refer to "the positive and negative side effects of mitigation policies and technologies" (Ürge-Vorsatz et al. 2014: 551). But this simplicity belies a complex array of assumptions and dimensions to co-benefits. Table 1, for example, illustrates the *twenty three* different terms used interchangeably with the term "co-benefits" identified by a recent review (Floater et al. 2016). Not even the Intergovernmental Panel on Climate Change (IPCC) has offered a consistent conceptualization of co-benefits in its own reports, with earlier assessments defining co-benefits as "benefits that are intended by the policymaker" but separating "ancillary benefits" as "unintended benefits" but merging them together in its latest 2014 assessment (Floater et al. 2016: 13-14).

Table 1: Terms used to describe the co-benefits of climate change mitigation in the literature

| No. | Term |
|---|---|
| 1 | Win-win situations |
| 2 | Life-cycle benefits |
| 3 | Triple-win scenarios |
| 4 | Consequential benefits |
| 5 | Ancillary benefits |
| 6 | Mutual benefits |
| 7 | Consequential life cycle impacts |
| 8 | Secondary benefits |
| 9 | Induced changes |
| 10 | Collateral benefits |
| 11 | Side benefits |
| 12 | Associated benefits |
| 13 | Spill-over benefits |
| 14 | Alignment of incentives/objectives |
| 15 | Mainstreaming |
| 16 | No-regret strategies |
| 17 | Co-priorities |
| 18 | Co-control |
| 19 | Synergistic objectives |
| 20 | Leverage points |
| 21 | Co-incidence of agendas |
| 22 | Externalities |
| 23 | Coupled systems |

Source: Modified from Floater et al. (2016).

Furthermore, such co-benefits can differ meaningfully in their intentionality, scope, and scale (Floater et al. 2016). The intentionality of a co-benefit refers to whether it is pursued actively as a primary, secondary, or integrated objective, or whether it occurs accidentally and unintentionally. The scope of a co-benefit relates to whether it occurs via climate change mitigation (stopping emissions), climate change adaptation (building resilience to the impacts of climate change), or both. The scale of a co-benefit relates to the sectors or stakeholders accruing the benefit, and how they may differ temporally (near-term vs. long-term) and geography (local vs. national vs. global). Co-benefits can also sit alongside costs or adverse consequences, with the IPCC noting that "a government policy or a measure intended to achieve one objective (such as mitigation) will also affect other objectives (such as local air quality) … to the extent these side-effects are positive, they can be deemed 'co-benefits'; otherwise they are termed 'adverse side-effects'" (Edenhofer et al. 2014: TS.11).

Ürge-Vorsatz et al. (2014) offer an authoritative review of the climate change co-benefits or co-impacts literature, and note that better documenting of co-benefits can help reveal some of the equity considerations often implicit or ignored in climate policy, especially tensions between current and future generations. Co-benefits also serve as entry points for mobilizing climate action by providing a focal point for groups advocating for climate policies. This may be especially true when the benefits from climate mitigation can translate into trillions of dollars of avoided damages, or significant welfare gains to households, firms, and even nations (Burke et al. 2018; Noel et al. 2018; Alberni et al. 2018; Sovacool et al. 2017; Achtnicht 2011). The IPCC itself categorizes co-benefits into the three classes of "economic," "social," and "environmental" shown in Table 2 (Edenhofer et al. 2014).

Table 2: Overview of potential co-benefits to climate change mitigation across energy supply, transport, and buildings

| Sector | Economic co-benefits | Social co-benefits | Environmental co-benefits |
|---|---|---|---|
| Energy supply | | | |
| *Nuclear replacing coal power* | Energy security (reduced exposure to fuel price volatility)<br><br>Local employment impact (but uncertain net effect) | Health impact via decreased air pollution<br><br>Health impact via decreased coal mining accidents | Ecosystem impact via reduced air pollution and coal mining |
| *Renewable electricity (wind, solar, hydro, geothermal, bioenergy) replacing coal* | Energy security (resource sufficiency, diversity in the near/medium term)<br><br>Local employment impact (but uncertain net effect)<br><br>Irrigation, flood control, navigation, and water availability (for multipurpose reservoirs and regulated rivers) | Health impact via reduced air pollution (except bioenergy)<br><br>Health impact via decreased coal mining accidents<br><br>Contribution to off-grid energy access | Ecosystem impact via decreased air pollution (except bioenergy)<br><br>Ecosystem impact via decreased coal mining<br><br>Decreased water use (for wind and solar) |

| | | | |
|---|---|---|---|
| *Fossil carbon capture and storage (CCS) replacing coal* | Preservation vs. lock-in of human and physical capital in the fossil fuel industry | | |
| *Methane leakage prevention, capture, or treatment* | Energy security (potential to use gas in some cases) | Health impact via reduced air pollution<br><br>Occupational safety and coal mines | Ecosystem impact via reduced air pollution |
| Transport | | | |
| *Reduction of fuel carbon intensity via electricity, hydrogen, biofuel, and other fuels* | Energy security (diversification, reduced oil dependence and exposure to oil price volatility)<br><br>Technological spillovers (e.g. battery technologies for consumer electronics) | Health impact via urban pollution (net effect unclear) or reducing most pollutants (especially for electricity)<br><br>Health impact via reduced noise (electricity and fuel cells especially) | Ecosystem impact of electricity and hydrogen via urban air pollution |
| *Reduction of energy intensity* | Energy security (reduced oil dependence and exposure to price volatility) | Health impact via reduced noise (electricity and fuel cells especially)<br><br>Road safety via increased crash-worthiness | Ecosystem and biodiversity impact via reduced urban air pollution |
| *Compact urban form and improved infrastructure* | Energy security (reduced oil dependence and exposure to price volatility)<br><br>Productivity (reduced urban congestion and travel times, affordable and accessible transport) | Health impact for non-motorized modes via increased physical activity | Ecosystem impact via urban air pollution |
| *Modal shift* | Employment opportunities in the public transport sector vs. car manufacturing | Noise (modal shift and travel reduction)<br><br>Equitable mobility access to | Ecosystem impact via decreased land use competition |

| | | | |
|---|---|---|---|
| | | employment opportunities, particularly in developing countries<br><br>Road safety via infrastructure for walking and cycling | |
| *Journey distance reduction and avoidance* | Energy security (reduced oil dependence and exposure to price volatility)<br><br>Productivity (reduced urban congestion, travel times, walking) | Health impact (for non-motorized transport modes) | Ecosystem impact via urban air pollution<br><br>Land use competition from transport infrastructure |
| **Buildings** | | | |
| Fuel switching (incorporation of renewables, green roofs and other measures) | Energy security<br><br>Employment impact<br><br>Lower need for energy subsidies<br><br>Asset values of buildings | Fuel poverty reductions via energy demand<br><br>Productive time for women and children (for cookstoves) | Health impact in residential buildings via outdoor air pollution, indoor air pollution, and fuel poverty<br><br>Ecosystem impact (less outdoor air pollution)<br><br>Urban biodiversity (for green roofs) |
| Retrofits of existing buildings, new buildings, or installation of efficient equipment | Energy security<br><br>Employment impact<br><br>Productivity (for commercial buildings)<br><br>Lower need for energy subsidies<br><br>Asset values of buildings<br><br>Disaster resilience | Fuel poverty (for retrofits and efficient equipment)<br><br>Thermal comfort (for retrofits and exemplary new buildings)<br><br>Productive time for women and children (for replaced traditional cookstoves) | Health impact via air outdoor and indoor air pollution<br><br>Improved indoor environmental conditions<br><br>Fuel poverty<br><br>Ecosystem impact (less outdoor air pollution) |

| | | | |
|---|---|---|---|
| | | | Water consumption and sewage production |
| Behavioral changes reducing energy demand | Energy security<br><br>Lower need for energy subsidies | | Health impact via less outdoor air pollution<br><br>Improved indoor environmental conditions<br><br>Ecosystem impact (less outdoor air pollution) |

Source: Modified from Edenhofer et al. (2014). Note: the original IPCC report also lists co-benefits of mitigation for industry and managing land use change and forestry, but these are not included in the paper as none of our cases involve forestry, only energy, transport, and (to a degree) buildings. The IPCC also listed co-costs, which are not reported in the table, and a section on "Other," which is also not reported.

As Table 2 indicates, beyond economic and climatic benefits that may result from a reduced dependency on increasingly expensive and scarce non-renewable resources, a growing body of literature suggests that (quantifiable) improvements in health metrics are another substantial co-benefit of low carbon pathways. The IPCC working group on adaptation argues that the health co-benefits from low carbon infrastructure include fewer deaths from heat waves and forest fires, better food security, and improved curtailment of disease epidemics (Smith et al. 2014). Balbus et al. (2014) quantify these as representing $40 to $198 of positive health value per metric ton of carbon dioxide mitigated by 2020. Rafai et al. (2013) analyzed the co-benefits of pursuing a global mitigation strategy to keep temperatures rises below 2°C, and found that under a strong deployment of clean and green energy (an aggressive emission mitigation strategy), expenditures on air pollution control would fall by €250 billion in 2050. Moreover, the study highlighted significant improvements in human health and average life expectancy because of these policy initiatives. The International Monetary Fund (IMF) similarly estimated in 2015 the cost of air pollution and associated health and economic damage that can be used to illustrate "avoided costs" when fossil fuels are replaced by clean energy (Coady et al. 2015: 2). The amount monetized was staggering: $5.3 trillion, or 6.5% of global GDP, with the largest subsidies in absolute terms in China ($2.3 trillion), the United States ($699 billion), and Russia ($335 billion). This has been confirmed in comparative assessments of wind energy versus natural gas (McCubbin and Sovacool 2013). Lastly, the World Health Organization (WHO) estimates that if half of the global households that still use traditional fuels and stoves switched to cleaner cooking sources, over a ten-year period, families would save $34 billion per year and generate an economic return of $105 billion per year (United Nations Development Program 2013).

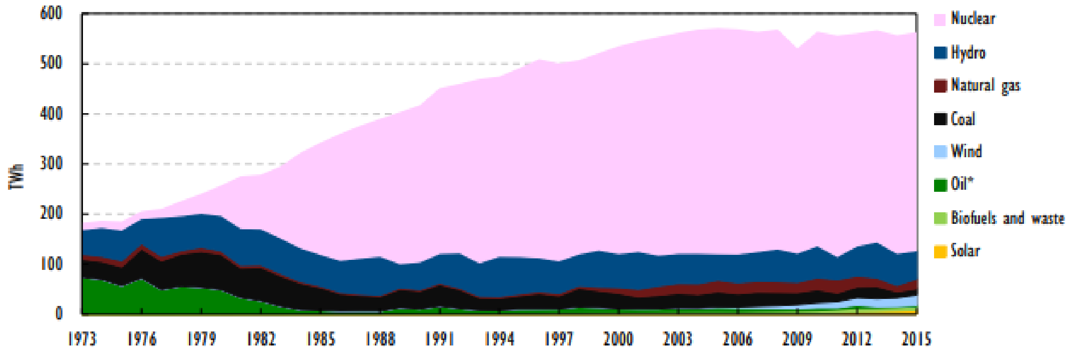
Indeed, scholars from other fields have conceptualized the co-benefits of policy choices as existing across many different dimensions. For Miyatsuka and Zusman (2010), co-benefits can be direct or indirect, as well as monetary or nonmonetary. They conceptualize “Level 1” co-benefits as those that are roughly proportional to the amount of investment made in targeting that policy change, such as jobs or improvements to health. “Level 2” co-benefits are more abstract and need not always be tied to the scale of investment and can relate to dimensions such as achieving energy security or independence from particular imports. “Level 3” co-benefits can refer to multiplier benefits that are interlinked with many causal factors and are not easy to quantify, such as enhancements to democracy or social status. Similarly, Creutzig et al. (2014) note the importance of non-quantifiable co-benefits such as the stabilization of the Eurozone as a possible co-benefit to climate change mitigation. When these disparate types, levels, and dimensions of potential co-benefits are “seen” in analysis, low carbon transitions can be recognized as delivering other net benefits to society such as entrepreneurship, resilience, and collectiveness.

### *2.2 Case study selection*

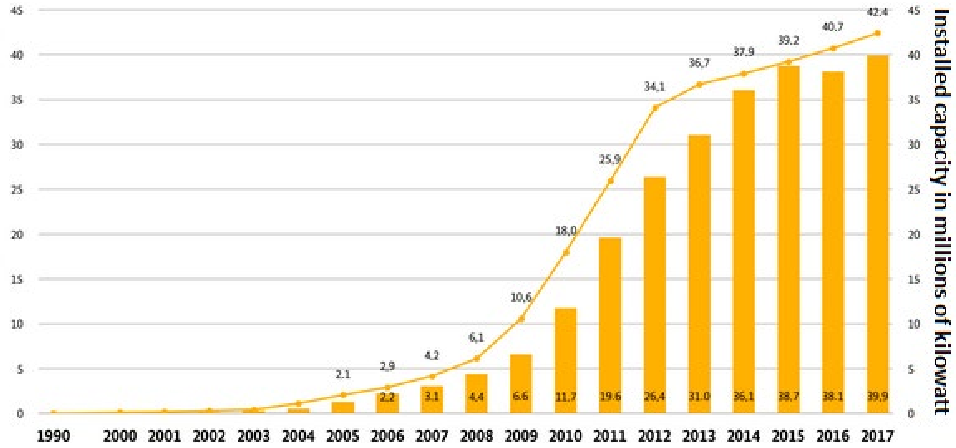
Acknowledging that low-carbon transitions can lead to a holistic array of co-benefits, cases were selected to represent a European or world leader in two sets of low carbon technologies, two supply oriented (nuclear power, solar PV) and two demand/end-use oriented (EVs, smart meters). The cases also portray different timescales in terms of initiation (nuclear power in the 1970s, EVs in the 1990s, solar PV in 2000s, and smart meters in the 2010s), as Figure 1 indicates.

**Figure 1: European low carbon energy transitions nuclear power (France), solar energy (Germany), smart meters (Great Britain), and electric vehicles (Norway)**

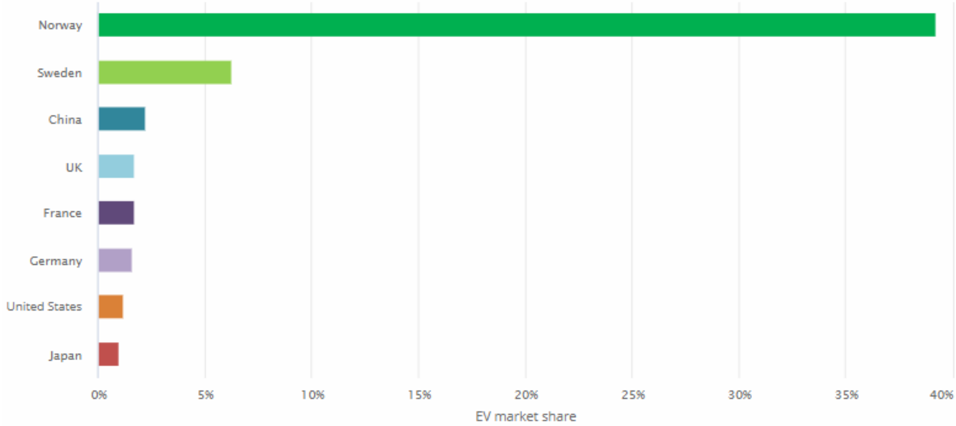
a. *Nuclear energy in the French electricity mix*



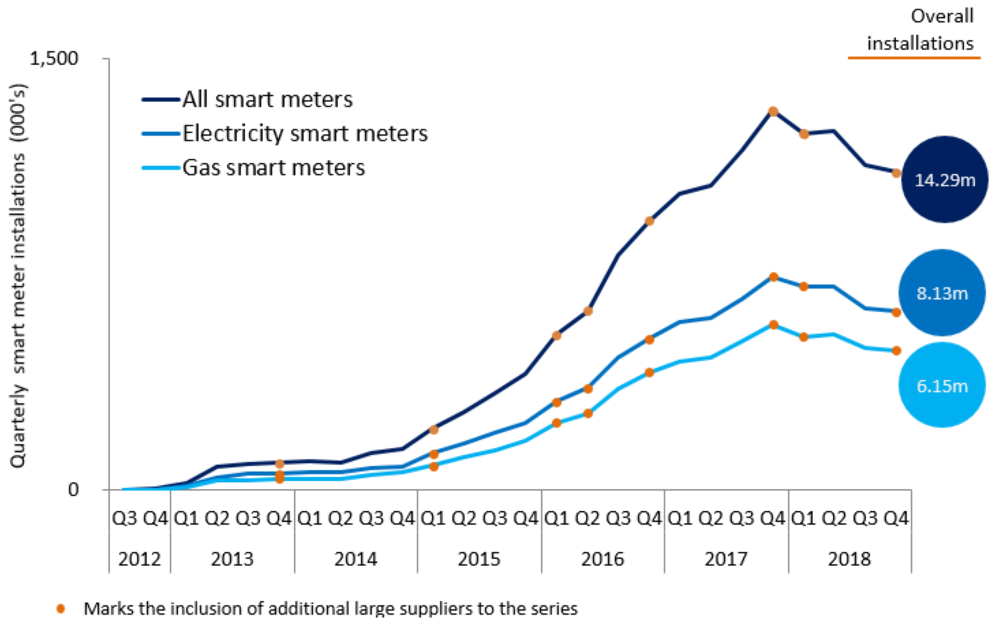

b. *Solar photovoltaic (PV) capacity in Germany*




c. *Electric vehicle market share in the top eight countries, 2017*




d. *Smart meter installations in Great Britain*




Source: Authors' compilation of most recent data from the International Energy Agency (for Norway and France), Federal Ministry for Economic Affairs and Energy (BMWi) for Germany, and the Department for Energy Business & Industrial Strategy for Great Britain.

France was chosen because it has a strong history of state-led nuclear power development that has made it a European leader for decades (Hecht 1988; Jasper 1992; Finon and Staropoli 2001; Sovacool and Valentine 2012). France relied on nuclear power plants for 4% of their national electricity supply in 1970 but currently receives about 75% of its electricity from nuclear power—the highest share of any major economy in the world—and comes second, after the United States, in its total number of reactors with 58 (compared to 104 in the United States) (World Nuclear Association 2018). It is the largest global exporter of nuclear electricity, transmitting 18% of its total production to Belgium, Germany, Italy, the Netherlands, and the United Kingdom, generating more than €3 billion in annual revenue. France is also one of the world's largest recyclers of nuclear fuel, with 17% of national electricity coming from reprocessed fuel rods (World Nuclear Association 2018). The French nuclear power program has therefore been hailed as "a success story" that has placed the country "ahead of the world" at building nuclear reactors and generating nuclear electricity (Weaver 2008: 12).

Germany was selected because it has one of the highest total per capita capacities of solar PV installed anywhere in the world, with 43,000 MW installed at the end of 2017, providing 7.2 % of gross national supply (Fraunhofer ISE, 2018).  This means that, strikingly, 41% of Europe's solar PVs are installed in Germany, with the next closest country (Italy) having only 19% of the EU market (German Federal Ministry for Economic Affairs and Energy 2017). A substantial number of these solar PV installations are not large-scale 'solar farms' but are distributed across homes and businesses, with Wittenberg and Matthies (2016) reporting that more than 1.5 million residential households own their own German system to take advantage of the country's feed-in tariff.

Norway was selected because it is the world leader in the per capita deployment of battery-powered electric vehicles, or EVs. The International Energy Agency (2018) notes that, thanks to Norway, the Nordic region saw the total stock of EVs reach 250,000 cars by the end of 2017, meaning that the region accounted for 8% of the global total, the third-largest share after China and the United States. The per capita diffusion of EVs across the Nordic region is the *highest* in the world at 10.6%; the growth rate the highest in the world (up 57% from the previous year); and Norway saw EVs representing 39% of annual new car sales (International Energy Agency 2018). As Ryghaug and Toftaker (2014: 146) write, "Norway is one of the world's leading electric car societies where the transition to electric road transport is most advanced, with many more electric cars than any other European country."

Finally, Great Britain was selected because of its aggressive national smart meters program—which will install digital meters that can track consumption instantaneously for electricity and natural gas—that began to be rolled out across England, Scotland, and Wales in 2016. This program, formally known as the Smart Meter Implementation Program (SMIP), lays the legal foundation to offer every home and business a smart meter by the end of 2020. It represents the British government's "flagship energy policy" and involves installing more than 50 million meters at a cost of at least £11 billion (Sovacool et al. 2017: 768). Although the expected costs and benefits of the rollout are debated, Lewis and Kerr (2014: 3) have argued that the SMIP is "by far the most complex" and also the "costliest" smart meter program in the world, as well as the largest government-run information technology project in history. Smart Energy Great Britain, the "voice" of the smart meter roll-out, framed it as "the biggest behavioral change program that this country has seen" and "the biggest national infrastructure project in our lifetimes" (House of Commons Science and Technology Committee, 2016: 13). The Department for Business, Energy & Industrial Strategy (BEIS, 2018) reported that 10.8 million smart meters were installed as of March 2018, corresponding to about 19% of the target number of 56 million. This makes Great Britain an obvious frontrunner in the deployment of smart meters.

### *2.3 Mixed methods research design*

With our cases selected, we proceeded with a qualitative research design that mixed methods across three approaches: semi-structured research interviews with experts, to obtain expert opinion; five focus groups in non-capital areas, to obtain public opinion; and the monitoring of twelve internet forums (three per country), to solicit public opinion beyond the somewhat limited scope of the focus groups.

We conducted 64 interviews, 16 per country, and sought to obtain a diverse mix of data from across academic institutions, non-profit organizations and civil society groups, government departments (including independent regulators), think tanks, and industry (including trade bodies and financial institutions) in the summer and fall of 2018 (see the data tables in Appendix I). In each interview, we asked (among other questions): "What do you see as the most significant benefits or advantages to the energy transition being examined?" The research interviews generally lasted between thirty and ninety minutes, were digitally recorded, and participants were guaranteed anonymity to protect their identity and encourage candor.

To supplement our expert interviews with public perceptions, we conducted five focus groups in non-capital areas of each country, namely Lewes (GB), Colmar (France), Freiburg (Germany), and Stavanger (Norway) with a total of 15 participants, summarized also in Appendix I. The justification for focus groups was to solicit input from non-expert stakeholders, given that focus groups and interviews work well together, but are not substitutes. Interviews tend to reveal more private, in-depth opinions, whereas focus groups reveal more public attitudes and consensus values (Kaplowitz and Hoehn 2001; Gailing and Naumann 2018). Admittedly, our focus groups were on the small side, with two to six participants each, whereas Citizens Advice (2015) suggests an optimal size of 6 to 8 respondents and O'Nyumba et al. (2018) report a common size of 3 to 21 participants. However, Morgan (2012) emphasizes in particular the value of smaller 2 to 3 person focus groups, for being more intimate and having a better group dynamic, which we certainly found to be the case in our research design and implementation.

Lastly, to triangulate our interviews and focus groups, we posted research questions on online internet forums, three per country, to solicit public input beyond the focus groups. Collectively, these forums had almost 2.1 million members that we could identify (see Appendix I for more details). For each case study, we asked: "What are the biggest advantages of low carbon innovations such as smart meters, EVs, solar PV, or nuclear? Who are the big recipients of those benefits or winners?" This resulted in 58 additional responses.

After collection of the interview, focus group, and internet forum data, all audio and textual data were transcribed, with each respondent given a unique identifying number. All transcripts were then coded by two researchers. Our coding scheme was exhaustive and inductive, meaning we coded every response and then analyzed the full sample using NVIVO.

Our research design is meant to be seen as a complement, rather than a full substitute, to alternative approaches such as those using hedonic prices and willingness to pay research designs. These alternative approaches, while useful, have been critiqued for estimation biases whereby respondents overstate the amount they are willing to pay or contribute, or struggle to convert different preferences into monetary terms (Thampapillai 2002). Soderholm and Sundqvist (2003) add that willingness to pay methods do not work well when priorities or goals conflict, when a particular topic is multifunctional or multidimensional, or when it can provide a complex array of goods and services difficult to predict and monetize. This certainly seems to be the case with climate co-benefits, and so we selected a set of methods that would not overly restrict respondents and artificially narrow the resulting discussion.

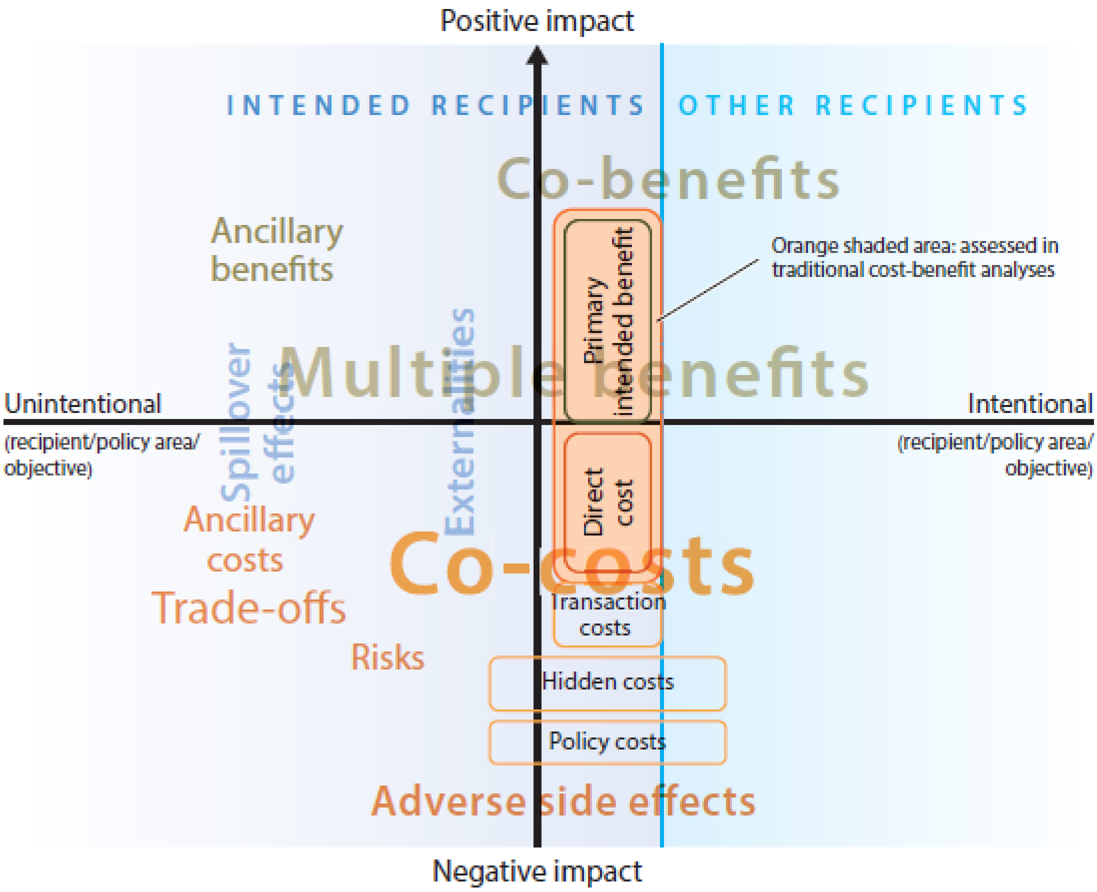
### *2.4 Limitations*

Despite an attempt to holistically conceive of co-benefits, and at triangulation within its research design, our approach does have some notable limitations.

Firstly, most rigorous co-benefit analyses, especially quantitative assessments, evaluate a co-benefit against a well-defined counterfactual. If looking at the provision of renewable electricity, for instance, a co-benefit study would evaluate that provision against a counterfactual of coal-fired power, which is how the IPCC has done it in their catalogue in Table 2 (above). Given that we asked respondents about benefits (which could be perceived, potential, or prospective), rather than those established by a consistent counterfactual analysis, our analysis is more qualitative and sometimes lacks any explicit baseline or alternative for a specific co-benefit.

Secondly, our study examines co-benefits but not adverse side effects or costs. This is rooted in the research question we asked—overtly about "benefits or advantages"—and it means we do not discuss possible mitigation costs alongside benefits, or barriers. Yet, as Edenhofer et al. (2014) convincingly argue, mitigation costs represent an important component of considering the relationship between climate change mitigation and human welfare, and such costs can be expressed in terms of changes in economic activity, consumption losses, compensating variation, and loss in consumer or producer surpluses. This is why much of the literature uses the term "co-impacts" rather than "co-benefits," as it encompasses co-costs, lifecycle impacts, or ancillary impacts, alongside positive aspects (Floater et al. 2016). Ürge-Vorsatz et al. (2014) even offer a helpful schematic diagram in Figure 2 showing positive *and negative* co-impacts to climate action, alongside intentional and unintentional consequences. Our study only assesses half of this typology, by focusing on what Ürge-Vorsatz et al. (2014) would call intentional and unintentional positive impacts (in the top half of the diagram). Moreover, by focusing only on co-benefits, we do not explore the likely barriers facing climate policy or action, and which could very well impede the realization or fair distribution of such benefits, such as market barriers and market failures (Brown 2001), path dependence and lock-in (Brown et al. 2007), the mobilization of finance (Polzin 2017), and patterns of incumbency that resist change (Geels 2012), to name a few.

Figure 2: A typology of positive and negative vs. intentional and unintentional co-benefits and co-impacts



Source: Ürge-Vorsatz et al. (2014: 555)

Thirdly, in terms of data collection, although the focus groups and internet forums were open to all members of the public, the number of responses collected was less than that of the expert interviews. Moreover, due to the wealth of empirical material spread across four case studies, we did not have sufficient space in this study to also assess barriers, or disadvantages, or to conduct a rigorous literature review to confirm our findings. We do, however, examine whole systems injustices and negative justice externalities affiliated with the four transitions in a separate paper. We also did not make an attempt to weight, correct, normalize, or problematize data across our methods, to avoid censoring our results and discussion.

## 3. Results: Beyond cost and carbon in the co-benefits of low carbon energy

Overall, our mixed methods results produced a total of 128 benefits that we inductively placed in technical, economic, political, social, and environmental dimensions. By technical, we refer to benefits such as efficiency and performance improvements, innovation dynamics, and knowledge and skills development. By economic, we refer to benefits including affordable energy services, revenues for stakeholders (including users and investors), and jobs. By political, we refer to benefits such as policy learning, enhanced energy security, and building political capital via meeting campaign pledges and promises. By social, we refer to improvements in comfort, prestige, identity, awareness, and lifestyle. By environmental, we mean benefits in terms of reduced air pollution, mitigation of emissions, water, and other aspects of the natural world.

Admittedly, these categories interrelate. As just one example, improvements in technical performance and patterns of positive innovation (which we classify as technical) also intersect with the types of energy goods and services being provided, and market structure (which many might classify as economic). We sidestepped this issue by simply classifying co-benefits on the terms and phrases used by our respondents. In this section, we elaborate further on the context-specific articulations of these benefits by each national case study, conducting frequency counts to determine benefits that recurred within the interviews. Then, in Section 4, we discuss more critically the issues that cut across these cases, offering some new theorizations of 'co-benefits' – as observable phenomena that may have under-acknowledged synergetic, temporal, spatial, social, and disruptive dimensions.

### *3.1 Nuclear power in France*

Our data led to the cataloging of 30 co-benefits in total to nuclear power in France, the most mentioned dimensions being technical (9) and economic (9), followed by social (5), environmental (4) and political (3). Table 3 offers an overview of these findings, as well as the frequency by which they occurred across our methods.

**Table 3: Identified co-benefits to the French nuclear power transition**

| No. | Type | Benefit | Supported by[a] | Frequency[b] |
|---|---|---|---|---|
| 1 | Economic | Cheap electricity for France | RI | 10 |
| 2 | Environmental | Low carbon energy source | RI, IF | 10 |
| 3 | Economic | Created well-paid and stable jobs in nuclear industry | RI | 9 |
| 4 | Political | Secured energy independence and energy security, reduced fossil fuel imports | RI, IF | 7 |
| 5 | Social | Supported egalitarian energy access | RI | 7 |
| 6 | Social | Galvanized pride in national project | RI | 6 |
| 7 | Economic | Supported industrial growth | RI, FG | 6 |
| 8 | Technical | Facilitated nationwide electrification and heating | RI | 5 |
| 9 | Political | Supported articulation of national power | RI | 5 |
| 10 | Economic | Cheap electricity for neighbors and profitable exports | RI | 4 |
| 11 | Social | Enabled social investments in peripheral regions | RI | 4 |
| 12 | Environmental | A safe form of energy with risks well managed | RI | 4 |

| | | | | |
|---|---|---|---|---|
| 13 | Technical | Developed France's nuclear industry expertise | RI | 4 |
| 14 | Technical | Provides large baseload generation | RI | 4 |
| 15 | Economic | Sustained *péréquation tarifaire* | RI | 4 |
| 16 | Economic | Low variable costs per kwh | RI | 3 |
| 17 | Economic | Nuclear energy export revenue | RI, FG | 3 |
| 18 | Technical | Supported broader technological and industrial innovation | RI | 2 |
| 19 | Technical | Supports EU interconnection | RI | 2 |
| 20 | Technical | Complementary to renewable integration | RI | 2 |
| 21 | Political | Complemented France's political system | RI | 2 |
| 22 | Technical | Generated technical and best practice expertise and knowledge for transfer | RI | 2 |
| 23 | Environmental | Enabled France to phase out other carbon energies | RI | 2 |
| 24 | Environmental | Cleaner local air | RI | 1 |
| 25 | Social | Raising industry working standards | RI | 1 |
| 26 | Technical | Providing re-processing facilities for other countries | RI | 1 |
| 27 | Technical | Facilitated time of use system | RI | 1 |
| 28 | Economic | Low cost of decommissioning | RI | 1 |
| 29 | Social | Increase in thermal and home comfort | FG | - |
| 30 | Economic | Profitable returns for shareholders and investors | IF | - |

Source: Authors. Note: [a]RI=research interview. FG=focus group. IF=internet forum. [b]Frequency counts conducted only for the interviews, as the focus groups and internet forums did not have a fixed number of respondents.

The most frequently mentioned category of technical benefits included aspects such as broader industrial innovation, the building up of nuclear skills and capacity, and the development of a technically robust national network of electricity and heat provision. From a technical perspective, the broad development of nuclear energy established a French engineering expertise that became envied and exported worldwide (benefits 13 and 22), but also supported a broad national project of electrification and heating – creating innovations such as 'time of use' tariffing (benefits 8 and 27). These developments all had strong social benefits, as many newly-built households benefitted from improved thermal comfort that electrical heating brought. For some interviewees, such innovations – despite the claims that nuclear energy 'locks in' states technically to a nuclear (and centralized) path-dependence – put France at an advantage today as its broad electrification could potentially support other low carbon innovations such as electric vehicles and renewable energy integration (benefit 20).

The second most frequently mentioned category of economic benefits emphasized aspects such as cheap electricity for France (which has undoubtedly served as a backbone for economic growth and industrialization, as Figure 3 underscores), high-paying jobs, and cheap electricity for countries bordering France. Most expert interviewees recognized that, although electricity prices had risen in recent years, all French citizens had historically enjoyed the benefits of the nuclear transition in the form of cheap electricity (benefit 1). As F003 reasoned:

> *For people, electricity has been really affordable, and it has been a national business, so prices were decided politically. Nuclear really allowed us to develop French industries, and having access to cheap electricity has been very good for the development of the economy, as energy is life. Yes, it has been a choice, but that choice has been a main positive benefit.*

F012 estimated that because of nuclear power, Électricité de France (EDF), the state-owned utility, is able to employ 100,000 to 200,000 jobs necessary in managing the grid. The industrial and manufacturing sector was said to have also benefitted from cheap electricity, and nuclear energy supported a joined-up industrial strategy throughout the 1960s and 1970s that presided over the construction of the national railway network, as well as supporting the development of private French firms (benefits 7 and 18).

Figure 3: The Solvay/Butachimie industry platform in Chalampé, France, served partly by the Fessenheim nuclear power plant, July 2018

Source: Authors

Socially, nuclear power in France was acclaimed for bringing egalitarian energy access, galvanizing national pride, and raising industrial working standards. Because of the standardized national tariff, the *péréquation tarifaire*, all households across France have enjoyed (and continue to enjoy) an equally low rate of electricity, regardless of their remoteness or rurality (benefit 8). F014 summarizes this link:

> *There is the* péréquation tarifaire, *which is a cross-subsidy for rural users. This represents a conscious attempt to level prices. And there were measures to minimize inequalities in terms of cost and access to energy … the idea is to make sure everyone pays the same.*

F004 also highlighted this link:

> *One positive takeaway from the French nuclear program was the link made from the beginning between a technical option and public service policy. It was about a concern of social justice from the beginning.*

While nuclear energy may not be *directly* responsible for such a development, it undoubtedly helped France to sustain such a policy through the provision of massive baseload generation (benefit 14).

From an environmental perspective, the existence of the nuclear program was strongly credited with securing relatively low levels of $C0_2$ emissions within France's electricity generation (benefit 2). As F013 described:

> *Nuclear is clearly a low carbon technology, whatever perspective you take. On operation, it doesn't emit $C0_2$. If you consider the whole lifecycle assessment, it is probably with wind and hydro, the lowest carbon footprint you could imagine. Solar emits much more $CO_2$ if you consider the whole lifetime.*

As well as benefitting France, this contributes to global emissions reductions: indeed, according to an EC JRC and PBL (2015) report, France had the lowest $CO_2$ emissions per capita within the OECD as of 2014. On a local level within France, respondents noted how a broad "low carbon" electricity baseload also secured cleaner air, benefitting public health and the local environment (benefit 24), particularly as the development of nuclear energy enabled the phasing out of other "dirtier" energy production sources, such as coal (benefit 23).

Politically, the benefits of the nuclear transition were regarded as strongly accruing to the centralized state, for which nuclear energy was considered a perfect complement (benefits 9 and 21). F002 even went as far as to claim that nuclear energy had become central to France's identity as a country, providing it with a source of national pride and patriotism in the second half of the twentieth century:

*Nuclear energy locked into a sense of nationhood and pride in engineering, which is also linked into the military aspects of the program, which themselves were the result of feelings of shame or disempowerment during World War II. Out of that conflict emerged a sense of needing a place at the table and an articulation of national power.*

More practically, as well as the vast numbers of jobs created within (and around) the plants themselves, the nuclear industry reinforced and secured the future of the cadre of trained specialists (such as engineers and economists) within the *Corps des Mines* in Paris, who continue to administer the nuclear program (benefit 3). Finally, some interviewees considered that the energy independence that France had gained through the existence of its nuclear energy source had also minimized its vulnerability to external price shocks and its need to engage in risky commercial and military foreign activities in order to secure supplies of oil and gas (benefit 4).

### *3.2 Solar PV in Germany*

Our respondents identified 30 distinct benefits to solar energy in Germany, the most popular category being economic (9) followed by political (6), social (6), technical (6) and environmental (3), as summarized in Table 4.

Table 4: Identified co-benefits to the German solar energy transition

| No. | Type | Benefit | Supported by[a] | Frequency[b] |
|---|---|---|---|---|
| 1 | Economic | Created new businesses and jobs in manufacturing | RI, FG | 13 |
| 2 | Environmental | Emissions reductions | RI, FG, IF | 12 |
| 3 | Social | Enables citizen energy democracy | RI, FG | 12 |
| 4 | Economic | Profitable for investors | RI | 12 |
| 5 | Economic | Has reduced costs for PV | RI, IF | 9 |
| 6 | Political | More decentralization | RI, FG | 8 |
| 7 | Technical | Development of German innovation | RI | 8 |
| 8 | Economic | Created a PV market | RI | 7 |
| 9 | Social | Generating awareness in renewables | RI, FG | 7 |
| 10 | Social | Participation in policy | RI | 6 |
| 11 | Economic | Reduced electricity costs | RI, FG, IF | 5 |
| 12 | Political | Lessons about transitions | RI, FG | 5 |
| 13 | Political | Minimizes dependence on fossil fuels | RI, FG | 5 |
| 14 | Technical | Learning by doing | RI | 4 |
| 15 | Economic | Easy process for installers | RI | 3 |
| 16 | Environmental | Does not impact on landscape as much as some other technologies | RI, FG | 3 |
| 17 | Political | National energy independence | RI | 3 |
| 18 | Political | People achieving autonomy | RI | 3 |
| 19 | Technical | Creation of decentralized producers | RI | 3 |
| 20 | Economic | Made use of farm land and other land | RI | 2 |

| | | | | |
|---|---|---|---|---|
| 21 | Economic | Surplus energy production being exported | RI | 2 |
| 22 | Economic | Tax revenue from solar users | RI | 1 |
| 23 | Technical | Demonstrated feasibility | RI | 2 |
| 24 | Political | Energy leadership opportunity | RI, FG | 1 |
| 25 | Social | Domestic comfort | FG, IF | - |
| 26 | Social | Health benefits | RI | 1 |
| 27 | Social | Protects rural communities | RI | 1 |
| 28 | Technical | Better EU interconnection | RI | 1 |
| 29 | Technical | Facilitating move to renewables | RI | 1 |
| 30 | Environmental | Making use of natural endowments for energy | FG | - |

Source: Authors. Note: [a]RI=research interview. FG=focus group. IF=internet forum. [b]Frequency counts conducted only for the interviews, as the focus groups and internet forums did not have a fixed number of respondents.

The most frequently mentioned economic benefits of solar PV in Germany were the creation of new businesses and jobs in manufacturing (benefit 1) and the fact that solar PV is profitable for investors, whether small or large-scale (benefit 4). At the height of Germany's solar PV industry in 2012, one respondent claimed that the sector had approximately 120,000 jobs[1] (G004). The International Renewable Energy Agency (IRENA) (2018) reports that global renewable energy employment reached 10.3 million jobs in 2017, and that it was approximately 325,000 jobs in Germany overall, a slight increase from the earlier year, although it noted that it was the wind industry, not the solar industry, dominating jobs. For example, IRENA (2018) estimated that the 160,100 people working in Germany's wind energy industry equaled the number of employees in the next ten largest European countries combined.

The current German wind industry contrasts sharply with the German solar industry. While many of its jobs were lost following cuts to the feed-in-tariff (FIT) in 2012, the sector retained approximately 36,000 jobs as of 2016 (G013) and it continues to manufacture the technical machinery that is exported for use in the global production of panels. Things may get more optimistic in the future, with Lehr et al. (2012) projecting that gross employment in the German renewable energy sector will increase from 340,000 in 2009 to 600,000 by 2030.

Implemented through the German Renewable Energy Sources Act of 2000, the FIT law has provided a long-term investment opportunity for investors, guaranteeing income for 20

[1] Lütkenhorst and Pegels (2014) claim the number was nearer 90,000.

years (G010). The generous support of the FIT also resulted in another economic benefit, reduced costs for PV (benefit 5), which ultimately enabled Germany to create a domestic PV market (benefit 8), while also having a strong influence on both the development of innovation and the global PV market. As G014 noted:

> *When you look back at the cost regression of solar panels, Germany contributed very much to bringing solar worldwide to the market.*

In this way the German transition is credited with lowering the cost of solar energy in multiple markets (G004).

Social benefits centered on aspects such as energy democracy, generating awareness, and domestic comfort. The wide acceptance of solar PV amongst the German public (a result of what many interviewees attributed to the initially economically very attractive nature of the value proposition) has led the technology itself to have significant impacts on the political landscape of German energy markets. Indeed, it has enabled greater decentralization (benefit 6), and has enabled people to achieve a greater level of autonomy (benefit 18) through self-supply by allowing them to move away from the dominant energy suppliers – a potentially disruptive long-term dynamic (Richter 2013). This trend has brought several social benefits, such as generating awareness in renewables (benefit 9) and widening participation in policy (benefit 10) beyond incumbent players. However, the most frequently mentioned social benefit of solar PV was the way it has enabled a broader energy democracy (benefit 3) by providing people not only with an opportunity to take part in the German energy transition but also to do so on their own terms. As G011 stated:

> *I would say that the strengthening of democracy is a benefit of this transition to renewables, because we find that people are getting engaged in community projects, and when you read surveys about these projects, about why they participate in solar and wind projects, the motives vary and financial motives are an aspect but it is never the first. The biggest driver is that they want to do something good for the community, and that tells me that there is a wider benefit of democratization in society. That people are talking to each other and taking matters into their own hands. I think that is a big benefit that is overseen. The unique part of the process is the citizen-led nature of the transition.*

This community uptake of solar is illustrated in Figure 4, which shows a fairly large-scale solar system installed at a spa in Berlin.

Figure 4: A community solar PV installation at the Liquidrom Spa in Berlin, Germany, July 2018

Source: Authors.

Importantly, respondents underscored that Germany's experience with solar PV can provide valuable policy lessons about transitions (benefit 12) to other countries, showing how a transition could work (G005) for other industrialized nations (G008). There are also implications for national energy independence (benefit 17), as there is the potential for minimizing dependence on fossil fuels (benefit 13) in countries that rely mostly on imports of coal and gas for its electricity generation sources.

Technical benefits mentioned by respondents include the development of German innovation, learning by doing, and better connection with the European Union. Early market creation, especially before 2005, was built on the success of developing German innovation (benefit 7), notably in the manufacturing of solar panels which "*survived and thrived and drove technology in part because it was close to the application*" (G001), enabling learning by doing (benefit 14) as the technology and industry matured.

Lastly, respondents suggested that solar PV has brought environmental benefits to Germany in terms of emissions reductions (benefit 2) from increased use of renewable energy. Further, G008 discussed how solar brings benefits by enabling Germany to phase out nuclear, noting that "*beneficiaries or winners could be kids in the vicinity of nuclear power* *reactors or people who live in the vicinity of a nuclear waste dump, or anybody who's just not happy trains of nuclear waste running through the country."* While renewable energy is generally popular in Germany (G014), solar PV especially is widely accepted given that solar PV installations do not impact on landscape as much as some other technologies such as wind, nuclear, or coal (benefit 16).

### *3.3 Electric vehicles (EVs) in Norway*

Our original material led to the identification of 26 benefits associated with Norwegian EVs, led by economic (8) and social (7) and followed by technical (4), environmental (4), and political (3). Table 5 offers a summary.

Table 5: Identified co-benefits to the Norwegian electric vehicle transition

| No. | Type | Benefit | Supported by[a] | Frequency[b] |
|---|---|---|---|---|
| 1 | Environmental | Emissions reductions, climate change | RI, IF | 16 |
| 2 | Economic | Provision of concessions for owners | RI | 12 |
| 3 | Environmental | Air quality | RI | 12 |
| 4 | Technical | Demonstrating technology to others, stimulating innovation | RI, FG | 10 |
| 5 | Environmental | Noise reduction | RI | 9 |
| 6 | Political | Developing policy learning and innovation, a model for others | RI, FG | 8 |
| 7 | Social | Convenience of special rules, exceptions, saving travel time | RI, IF | 5 |
| 8 | Economic | Save money on fossil transport fuels | RI, IF | 4 |
| 9 | Economic | Encourages other private companies to enter the EV market | RI | 3 |
| 10 | Social | Enjoyable to use, comfortable to drive | RI, FG, IF | 3 |
| 11 | Political | Political objective on take-up met | RI | 3 |
| 12 | Economic | Export revenues from cars, parts sales | RI | 2 |
| 13 | Social | Stimulating greater environmental awareness | RI, FG | 2 |
| 14 | Social | Good for conscience | RI, FG | 2 |
| 15 | Technical | A good use of abundant electricity production | RI | 2 |
| 16 | Economic | Complementary companies benefitting from provision of EV infrastructure | RI | 1 |
| 17 | Economic | Electricity providers seeing higher demand | RI | 1 |
| 18 | Economic | EVs keep their value | RI | 1 |
| 19 | Political | Contributing to energy security and independence by minimizing need for oil | RI, FG | 1 |
| 20 | Social | Safer environment | RI | 1 |
| 21 | Economic | Enables cheaper car access and use | FG | - |
| 22 | Environmental | Leverages Norway's green and renewable electricity production | FG | - |
| 23 | Social | Freedom of movement | IF | - |
| 24 | Technical | More efficient conversion of energy, reduced fossil fuel usage | FG | - |

| | | | | |
|---|---|---|---|---|
| 25 | Technical | Improved reliability, fewer parts to go wrong | IF | - |
| 26 | Social | Prestige, a fashion statement | FG | - |

Source: Authors. Note: [a]RI=research interview. FG=focus group. IF=internet forum. [b]Frequency counts conducted only for the interviews, as the focus groups and internet forums did not have a fixed number of respondents.

The economic benefits cited by respondents included aspects such as saving money on fuel, the fact that EVs retain their financial value, and export revenues from the sales of cars and parts (benefits 8, 18 and 12). Twelve interviewees mentioned the provision of concessions for owners as key for those purchasing EVs (benefit 2). Indeed, EVs are presently exempt from purchase tax (calculated for each car depending on emissions and weight of the car) and value added tax (VAT is 25%). In addition to tax concessions, EV users also benefit from free charging, reduced rates on toll roads and ferries, and free parking. As N012 stated:

*There are multiple taxes that EV owners do not pay, VAT, purchase tax. I think you could say an expensive Tesla should have cost about 40-50% more with normal taxes, so it adds up to significant money. Still with free parking, reduced costs on the roads. They get a lot of money.*

These benefits are especially relevant to urban dwellers living close to the major cities of Oslo and Bergen, where EVs were initially seen as the wealthier person's car of choice, as N010 remarked:

*An abundance of rich single men with 2 or 3 cars, at least at the beginning, they were the winners.*

Admittedly, following the development of smaller and cheaper cars by makers such as Nissan and BMW, a wider population of Norwegians have been able to afford EVs, with N003 noting that "*they are (now) bought by any type of people, I don't think there is a strong social dimension to it here in Norway*" (N003). This perception was underscored in the focus group and internet forums, where it was emphasized that certain high-end brands were actually now more affordable in Norway in their EV versions, with Figure 5 showing an affordable model from Renault. Further illustrating this point, in the focus group, a respondent stated: "*I could never have afforded a regular BMW, but the EV is half the price.*" And in the internet forums, a respondent exclaimed: "*I almost get a heart attack when I have to use a fossil car, and then see the price for tanking (both in Norway and abroad).*"

Figure 5: A Renault Twizy Electric Vehicle in Oslo, June, 2018

Source: Authors

Social benefits included the fact that EVs are enjoyable, comfortable, and prestigious to own and drive (benefit 10), as well as the fact their wider diffusion sends signals to others that one is 'green' or 'environmentally aware'. N003 captured these sentiments about the experiential and emotional dimensions associated with owning and driving an EV:

> *Anyone who has an EV feels it is a better car, just more comfortable for the driver. That comes in addition to the environmental benefits. It is smoother, responds better to your signals, can drive as slow as you like or it accelerates easily, you have better control. Most people I know who have bought an EV say "Oh! It is so nice to drive." It works very quietly, compared to a traditional car with gears. If you drive in traffic jams, new cars have these anyway, but it is easy to stay in EV as easy to regulate distance due to the response.*

Social benefits were also mentioned in the focus groups, where respondents remarked on the role of EVs in raising environmental awareness, with one participant stating, "*people become green after buying an EV*". Another participant added that "*creating awareness is a big part of this*" and that interest had expanded from small groups of environmentally-motivated 'pioneers' to the wider public: "*before it was more hippies and Greenpeace, but now awareness is broader*". Driving comfort was mentioned repeatedly in the focus group, with one participant saying that her EV was "*a joy to drive*", while another highlighted that – especially in the early days of the market – EVs also brought a social prestige: "*EVs grew in Oslo as a fashion statement and as a more convenient way of traveling, in bus lanes*" (benefit 26). Freedom of movement came up in the internet forums too, with one user observing that, as EVs had free access to bus lanes, users could enjoy more stress-free journeys: "*it makes me less stressed, since I don't have to worry if a lane will turn into a bus lane*." Another noted that "*EVs are easy to drive, very relaxing*."

The technical benefits mentioned by respondents emphasized aspects such as the way in which EV development has stimulated broader innovation and the fact that EVs are a good fit for the Norwegian energy sector's technical base – where a large share of pumped-storage provides a clean and reliable basis of electricity. As N006 put it:

> *We tend to look at Norway as kind of a technical laboratory, what happens if we roll out EVs on a huge scale. The different car manufacturers send delegations here all the time to see how we handle this. How we handle charging, how it works, how people use their cars.*

Respondents in the internet forums highlighted the fact that EVs are technically more straightforward and have better reliability than regular cars (benefit 25). One respondent mentioned that with EVs, there were "*few things that can go wrong (less parts)*", while another highlighted that "*home charging is really simple. The cars have few parts that one needs to worry about (clutch, timing belt, exhaust).*" Another exclaimed that after an EV, "*I'll never go back to fossil car … when you get used to instant torque and good acceleration you just don't like the loud fossil engine struggling and screaming like a pig at full power*." Others remarked that EVs have "a *perfect drivetrain, no more slow and jerky gearboxes and start/stop systems, one-pedal driving is fantastic when you get used to it, I love having a full tank of electrons every morning;*" "*it is simply wonderful to drive an electric car, and passengers often marvel at how nice and smooth it feels*"; and "*using a fossil fueled car has become extremely unsatisfying. The motor annoys me considerably more now than before*."

The domain of environmental benefits from EVs encompassed aspects such as the role of EVs in mitigating climate change and in facilitating improvements in air quality and noise pollution (benefits 1, 3 and 5). Technical learning from the personal EV market was also seen as helping to expedite the electrification of other transport sectors, including buses, maritime and aviation. Emissions reductions from EVs were mentioned by all expert interviewees as a key environmental benefit. However, in addition to EVs contributing to emissions reductions at both global and national levels, a more localized benefit related to improvements in air quality – particularly important given that Norwegian cities have serious problems with air quality, especially in the cold winter months. As N012 noted:

> *Local air pollution is a huge driver for politicians promoting EV policies in cities like in Oslo, Bergen, Trondheim and so on. They have scores of air quality problems there. Taking out the nitrogen oxide is just as important as carbon dioxide in Norway.*

There are also benefits for city dwellers in terms of noise reduction, with N005 observing that "*the noise level goes down, at least in cities when the speed is low*".

The final domain of benefits relates to political dimensions, such as the generation of political capital, the contributions to energy security, and the production of policy learning for other countries. Indeed, with respect to the first of these benefits, three interviewees mentioned that some of the key beneficiaries of the Norwegian EV story have in fact been politicians – as their political objective on EV take-up has been comfortably met, enabling them to garner praise (even as some respondents acknowledged that the policy success had been somewhat accidental and unexpected). As N004 stated:

> *I am a bit proud actually of what we have done, because they set a goal and it has been a success.*

Policy success in Norway has also provided an opportunity for developing policy learning and innovation from the Norwegian case (benefit 6), with eight interviewees saying that Norway can act as an example for other countries who are interested in learning what does, and what does not, work in the development of an EV market and infrastructure. N005 especially highlighted that given the small size of Norway, "*the Norwegian example shows that if the incentives are strong enough, it's actually possible to see a large-scale electrification of the passenger car fleet*." Focus group participants also highlighted that EVs can bring political benefits, especially regarding energy independence:

> *It's also not just climate change, it's about diversifying beyond the two forms of energy today that power 80% of the world, and avoiding energy being produced in areas where there is conflict*.

### *3.4 Smart meters in Great Britain*

Finally, our material led to the identification of 42 discernable benefits for smart meters in Great Britain. At the top of the list were social (12) and technical (12) benefits, followed by economic (11), political (4) and environmental (3). Table 6 offers a summary of these benefits.

Table 6: Identified co-benefits to the Great Britain smart meter transition

| No. | Type | Benefit | Supported by[a] | Frequency[b] |
|---|---|---|---|---|
| 1 | Economic | Help households save money by identifying energy efficiency measures, controlling energy use | RI, FG, IF | 13 |
| 2 | Economic | Help households save money by enabling time of use | RI, IF | 10 |
| 3 | Environmental | Will facilitate more decarbonized energy system, integration of renewables | RI, IF | 11 |
| 4 | Environmental | Will reduce overall energy usage | RI, FG, IF | 11 |
| 5 | Social | Wider energy awareness and visibility | RI, FG | 11 |
| 6 | Technical | Facilitates distributed generation | RI | 9 |
| 7 | Social | Protects customers from shock or estimated bills | RI | 8 |
| 8 | Political | Policy learning | RI | 8 |
| 9 | Technical | Facilitates better demand management | RI, IF | 7 |
| 10 | Economic | Cheaper grid costs | RI, IF | 7 |
| 11 | Economic | Generation of data that can be valuable | RI, IF | 7 |
| 12 | Technical | Facilitates demand led energy system, innovation | RI, IF | 6 |
| 13 | Technical | Facilitates a more efficient grid, grid security | RI, IF | 5 |
| 14 | Social | Saves customers the inconvenience of reading meters | RI | 5 |
| 15 | Economic | Generates new sources of profit | RI | 5 |
| 16 | Economic | Saves money in meter reading and calls | RI | 4 |
| 17 | Political | Offers consumer protection through transparency | RI | 4 |
| 18 | Social | Makes it easier to pay bills | RI | 4 |
| 19 | Technical | Enables smart appliances | RI | 4 |
| 20 | Technical | Facilitates renewable integration | RI, IF | 4 |
| 21 | Environmental | Reduces emissions from meter reading | RI | 3 |
| 22 | Social | Enables the identification of vulnerability | RI | 3 |
| 23 | Social | Protects consumers from losing power by enabling credit extension | RI | 3 |
| 24 | Economic | Drives market competition | RI | 2 |
| 25 | Political | Enable national energy independence | RI | 2 |
| 26 | Technical | Facilitates nationwide and EU-wide grid integration | RI | 2 |
| 27 | Social | Removes uncertainty around energy consumption | RI | 2 |
| 28 | Social | Installation and tailored energy advice | RI | 2 |
| 29 | Economic | Help households save money through automated switching | RI | 2 |
| 30 | Technical | Facilitate EVs and storage | RI | 1 |
| 31 | Social | Minimizes vulnerability created by blackouts | RI | 1 |
| 32 | Social | Enables poorer households to consume more energy for no extra cost | RI | 1 |
| 33 | Political | Policy success | RI | 1 |
| 34 | Technical | Enables smart homes | RI | 1 |
| 35 | Economic | Drives a more cost-reflective energy system | RI | 1 |
| 36 | Economic | Identify fraudulent use, theft reduction | RI, IF | 1 |
| 37 | Economic | Creation of jobs for installers | FG | - |
| 38 | Social | Alerting people of possible incidents with elderly friends and family | FG | - |
| 39 | Social | Minimizing the need for elderly people to regularly deal with meter readers | FG | - |
| 40 | Technical | Quicker detection of faults | IF | - |
| 41 | Technical | More accurate bills | IF | - |

| | | | | |
|---|---|---|---|---|
| 42 | Technical | More secure than traditional meters | IF | - |

Source: Authors. Note: [a]RI=research interview. FG=focus group. IF=internet forum. [b]Frequency counts conducted only for the interviews, as the focus groups and internet forums did not have a fixed number of respondents.

Social benefits were (perhaps surprisingly) tied with technical benefits for the most mentioned category. These social benefits related to the widening in awareness and visibility of energy consumption (see Figure 6), as well as the more practical benefits associated with making it easier to pay bills and the positive effects on vulnerable communities, blackouts, and those in poverty. Many stated benefits result from the promise of more accurate bills. One important aspect of this is the potential end to 'shock' estimated bills and the uncertainties that have been associated with energy consumption and billing, which are one of the biggest sources of historical stress for more vulnerable energy users (benefits 7 and 27). As well as more accurate bills based on real-time consumption, customers are also already reportedly benefitting from being saved the inconvenience of having to read meters (benefit 14). In the focus groups, participants remarked how smart meters could particularly help elderly people:

> *I suppose if an older person was in trouble, and didn't use the energy that they were expected to use on a certain day, that could that somehow alert the company to think 'are they lying on the floor? They haven't turned the TV or cooker on…' and send someone to check on them.*

Elderly people may also prefer the fact that meter readings now also no longer need to be taken, as regular home visits by strangers were cited as a source of anxiety for many (benefits 14, 39).

**Figure 6: A first generation British Gas smart meter in-home display for electricity and heat visualizing household consumption in real-time**


Source: Authors

Proclaimed technical benefits span a range of activities including: the facilitation of demand response and distributed generation, efficiency improvements to grids, quicker detection of faults, and the enabling of smart homes and appliances. GB015 focused on the technical benefits of pre-paid meters, highlighting how these are ineluctably bound with social and economic dimensions:

> *A big beneficiary are pre-payment customers. It blows my mind to see videos of old ladies crawling in the road to top up her pre-payment meter. With a smart meter you can top it up online, on a phone, etc. Also, at the moment, switching between pre-payment and credit requires someone to install a brand-new meter, which is hugely expensive… The cost of the 'pay zone' system for pre-payment is hugely expensive. As a result, pre-payment customers, who are often the most vulnerable, are paying between £100 and £200 more for their energy than credit customers. Once you can reduce those costs, which smart meters do… those pre-payment customers can start saving money with a smart meter.*

In this way, smart meters were said to have positive synergies with other innovations such as advancements in payment plans.

Economic benefits are admittedly intertwined with some of the technical features of smart meters. The most mentioned benefit was that consumers with smart meters ultimately save money by using the data generated by the smart meter to identify ways in which they could save money on their energy consumption (benefit 1). This relates to the classic (though somewhat contested[2]) idea of energy monitoring and feedback, whereby an increased (and interrelated) level of energy visibility and awareness (benefit 5) leads consumers to change their energy use habits, switching off appliances and using energy more strategically. Although some interviewees pointed out that poorer households may already be monitoring their energy use very closely (and so would have limited opportunities for making *further* savings), others stressed that smart meters could facilitate a de-mystification of energy, with usage becoming more (literally) visible, through the changing colors of the In-Home Display (IHD). As well as leading to reduced bills through more prudent usage of energy, it may also facilitate greater thermal benefits as customers use energy more strategically – getting more heat for less money (benefit 32). As "*being able to quantify potential energy savings makes it a more compelling figure.*" GB09 argued that the data generated by smart meters could also be used to make a more persuasive case for making investments in energy efficiency– measures which could enable further financial savings. Smart meters could enable more decentralized generation by facilitating 'peer to peer' energy generation and trading (benefits 6 and 15).

Political benefits included policy learning, national energy independence, and meeting campaign promises. As GB007 stated:

> *If the government achieves it, the smart meter program will be held as a flagship initiative that we have led the world on, and they will talk about it as being a policy success.*

GB015 framed political benefits more in terms of energy security:

> *Geopolitically, you can look at how better management of our energy is going to affect the extent we need to continue demanding energy from overseas. Smart meters have the potential to minimize our dependence on foreign pipelines and resources*.

In this way benefits extended well beyond only households and small businesses.

Environmental benefits meanwhile centered on dimensions such as the continued decarbonization of electricity, the integration of renewables, and reduced overall energy use. Some interviewees maintained that smart meters are an essential component of the move towards more cost-efficient and ultimately less carbon-intensive electricity and energy generation and supply. As GB012 stated strongly:

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[2] See for example Buchanan et al. (2015).

*I do not understand how you can expect to coordinate energy supply and demand effectively and most cheaply, in terms of prices for customers, without smart meters.*

Furthermore, on the demand-side, more efficient energy usage stimulated by behavior change may in turn (for those customers who were not already under-consuming energy, at least) lead to overall more efficient (and lower) energy usage, and a positive environmental benefit through lower emissions (benefit 4). As GB007 remarked, "*anything that reduces energy demand will reduce the carbon intensity of the grid.*" Provided the energy generated continues to be progressively decarbonized, these will be benefits that will accrue to all, within the UK and beyond. Locally, there could also be an end to the carbon footprint and air pollution generated by the need for regular meter readings (benefit 21).

## 4. Discussion: Scale, temporality, spatiality, actors and incumbency

This section of the paper focuses inductively on more deeply analyzing and theorizing the co-benefits across our cases according to six cross-cutting themes or dimensions: complementarity, temporality, spatiality, actors, and incumbency.

### *4.1 Complementarity: interoperability and co-synergies with other innovations*

This category of benefits relates to how each particular low carbon technology being examined can create positive synergies with other low carbon technologies or practices. For example, although doubted by some respondents, nuclear power in France was credited by several others with enabling the integration of intermittent renewable sources of electricity such as wind and solar. As F005 noted:

*The advantage of nuclear is that it is baseload production, it is not intermittent. It runs regardless of the weather. It is very complementary to intermittent renewable resources, it is a tool for climate change prevention.*

Similarly, F015 stated:

*Going towards a low carbon electricity system is a huge challenge that is probably under-estimated by most. To achieve that you will need everything possible: more inter-connection between nuclear and solar PV, other renewables, more demand side management. The solution will be a combination of those technologies and services.*

Although some environmental activists in France have become resistant to the notion of expanding the use of EVs in France (because EV expansion is seen by them as being used by the nuclear lobby to support the argument for *further* nuclear expansion in order to power

EVs), it is undeniable that nuclear energy has *some* potential to be complementary – rather than antagonistic – to the development of certain renewable innovations (as argued judiciously in Cany et al. 2016).

Similarly, German solar panels were framed as being potentially synergetic with electric heat pumps, electric mobility and household storage. G001 remarked that:

> *Renewable electricity is shifting into the transport sector and shifting in to the heating sector. We do have a rise in electricity mobility. We have over 4 million EVs in Germany if you count e-bikes and e-scooters. And we have increasing number of heat pumps, which is a conversion of electricity.*

Indeed, Germany has an aim of being greenhouse gas-neutral by 2050 (BMU, 2018), and its transport and heating sectors especially could benefit from the potential co-synergies with solar PV (and other renewables), given that Germany is, as one interviewee conceded, "*not doing well in our climate change targets because the heating and transport sector is not doing well*" (G007). Other benefits discussed included prosuming and coupling solar panels with home energy storage.

In Norway, respondents suggested that EVs could be a first step towards the entire transformation of the transport and mobility system. As N006 speculated:

> *The EVs we see today are really only stepping stones towards more sophisticated integrated transportation system where an electric pod picks you up where you live and takes you to a hub where you get on a bigger bus, or whatever, and that takes you to a smaller pod again which will take you to exactly where you want to go. You see these presentations all the time and it seems obvious it is going to that direction.*

N015 claimed that this could bring potential co-synergies between more integrated personal and public transport:

> *We are looking at how to integrate EVs with walking and cycling more as part of public transport, but also how to integrate towards sharing solutions. That could be towards carpooling or Uber-type solutions. We are also developing technologies towards autonomous, smaller units. Which is more of an on-call type of service and with all these we believe, in not that many years down the road, public transport will look very different from today. It will be based on zero emissions solutions that are also public and individualized.*

Here, there is clearly the potential for EVs to coupled or combined with other innovations such as ridesharing, mobility as a service, and automated (driverless) cars (Firnkorn & Müller 2015; Axsen and Sovacool 2019).

Smart meters were identified as enabling peer-to-peer energy trading as well as EVs and integration of renewables. Respondents noted that consumers in Great Britain could combine smart meters with dynamic tariffs with EVs, storage, automated appliances, etc. to save money and to participate in the move towards a less carbon intensive grid by purchasing energy when it is cheapest (and less carbon intensive, i.e. at non-peaks times of day). As GB015 commented:

> *EVs are essentially a battery on wheels. With a smart meter, smart charger and EV, you can power your house from your battery during peak demand, getting free energy, and not taking energy from the grid. And then you can charge it at night, perhaps automatically, easing pressure on the grid, and saving money. Smart meters and EVs become a borderline utopian product.*

Respondents also noted that smart meters could enable more decentralized generation by facilitating "peer to peer" energy generation and trading, with the generation of more tangible data presenting a more quantifiable figure that lends itself to being traded.

### *4.2 Temporality: Beyond the immediate and intergenerational issues*

Our data shows how the collective benefits have strong temporal dimensions, with some relating more to the past, others specific to the present, while others are more uncertain and contingent on a complex interplay of technical, economic, social, political, and policy factors.

Nuclear power in France was credited with generating significant historical benefits in the form of cheap electricity, but over time, these benefits have arguably diminished for subsequent generations. For example, because of a proliferation of new safety requirements caused by growing concerns over security and safety, the costs of decommissioning and waste management have risen over time (Schneider 2013). When added to the rising debt obligations and interest payments from financing costs incurred by the state in funding plant construction and maintenance, these costs are driving not only higher electricity prices for subsequent generations, but also the obligation for the state to raise general taxation. For some interviewees, the benefits may thus be structured by a strongly inter-generational dynamic, with future generations potentially not only *not* benefitting from cheap electricity, but also having to bear the rising costs of decommissioning and waste management.

In Germany, solar PV has benefitted those most who invested in the early days of the FIT scheme, as, although they had to pay for more expensive equipment and bear the greatest risks, they were compensated by the most generous levels of FIT. As G001 clarified:

> *In a way, the success of the German transition is about timing. Some households were lucky enough to pick the right site and buy the equipment at the right time when there was a discount in the market, but they still locked in the high FIT. People who invested at that time, they got in excess of 60% return on capital or shareholder funds, guaranteed for 20 years. It was insane.*

This notion of risk, timing, and longevity was actually built into the FIT itself, which guaranteed an income for 20 years, but had a sliding-scale model that reduced subsidies every year, disproportionately incentivizing and rewarding early adoption (Mendonca et al. 2009)[3]. As for long-term benefits, G004 noted that the main benefit would be "*future generations benefiting from low carbon electricity production and mitigating climate change risk*".

In Norway, early beneficiaries of EVs were the wealthier segments of the population, who were able to benefit from being able to "signal" their own prestige and virtue. Potential future benefits could however spill over to other transport sectors such as maritime, aviation, and buses, especially as Norway takes advantage of its low carbon electricity production, 96.3% of which comes from hydro and pumped hydro as of 2016 (Statistics Norway, 2017). As N012 highlighted, Norway, in fact, has a vision of becoming the first fully electrical country in Europe, if not the world, and for the time being enjoys "*a huge surplus of electricity*" (N012).

For smart meters, the immediate benefits to the user relate more to the new visibility of energy use data and to corresponding behavior change and convenience. Many of the more long-term benefits relate to the transformations in the supply and generation side that could, in turn – and if enacted fully – lead to transformed opportunities for the consumer and for a range of supply-side actors (Pereira et al. 2018).

[3] This policy was eventually amended once policy makers realised that they had been too generous in the context of rapidly falling PV prices.

### *4.3 Spatiality and scale: beyond households or even countries*

Many of the presumed benefits cross multiple scales, in some cases extending well beyond the individual countries. In France, the massive surplus in electricity generation from nuclear plants is credited with enabling France to export energy to neighboring countries, leading to revenues accruing to the French state and allowing other countries to benefit from cheap energy imports (benefits 10 and 14). As F013 noted:

> *Nuclear technology transfer to China has worked really well. EDF is considered a very strong utility on safety, so they do international sharing of best practices. Our safety authorities also collaborate with other safety authorities and they do a lot of sharing.*

Other countries also benefitted from France's re-processing facilities, which enabled them to delay expenditure on expensive new programs in other energy areas (benefit 26).

Although the transfer of jobs away from Germany is seen by many as one of the most negative "subplots" of the solar PV story in the country, it is also true to state that the German solar transition benefitted manufacturers in other countries, especially, in China. As G003 remarked:

> *In a way, Germany with hundreds of billions of euros helped the Chinese to develop a new industry because everything was developed here in Germany and it was ready to market. Then the Chinese bought these technologies, bought these companies, or invented their own ones. In some cases, they even stole patents or copied technologies. They found a market that was ready here in Germany, based on our FIT system. They did not only copy or buy technologies that we have highly subsidized to become bankable and marketable, but they took over our market in Germany as well. At a certain point, 55% of all PV installed worldwide, globally, has been installed in Germany. Incredible. And I think most of the panels that have been sold in Germany are Chinese.*

G007 affirmed this point in stating that "*I think the German solar transition has been a very good program for China, actually!*" and that *"China has benefitted enormously."* Others recognized that the German solar FIT indirectly "*financed the learning curve for PV globally*" (G004), benefitted others in Europe (such as *"Greece, Spain, Italy, and the United Kingdom,")* (G005), and that it also holds potential for "*those who need solar PV for modern energy access in Africa and Asia*" (G006).

Norwegian EVs were similarly credited with meaningfully contributing to the development of a cleaner global passenger car fleet. As N006 remarked:

> *Other places and markets have a lot more to gain from the EV transition here environmentally than we do, because it was not so bad here to begin with, we are a sparsely populated country and most cars are not that old. But if China or Southeast Asia goes electric, that will have a much more positive impact.*

N016 supported this view, remarking that Norway has shown the world that an EV transition "*is possible*."

For smart meters, multiple respondents discussed how the program in Great Britain offered what GB007 called valuable "*lessons for other countries*." As GB016 remarked:

> *From an infrastructure perspective, the lessons, the budget, the business plan are all published and transparent. Other countries will look very closely at it because it is very transparent and accessible, they can see the costs and process, seeing what to do and not to do. In other countries there isn't the transparency or the infrastructure and there isn't the future-proofing that the DCC gives you. It is a big plus for everyone outside of the UK.*

Relatedly, GB008 talked about other governments that have not rolled out smart meters yet being "*shared learners*;" and GB011 stated that "*there are learnings based on the data that could be exported to other countries, in terms of benchmarking and monitoring*." GB014 meanwhile commented that "*other countries may look at Great Britain's roll out and draw some lessons from it.*" Finally, GB015 underscored that "*there's a cross-border trade in information*" resulting from the smart meter program.

### *4.4 Actors: beyond users or consumers*

Our data reveals that many of the benefits brought by low carbon transitions extend beyond the immediate energy or mobility actors (the users or consumers) to other actors across the supply chain. In France, jobs and amenities for communities near power plants were recognized as disproportionately accruing to the areas around the power plants, many of which were recognized as being otherwise "peripheral" and under-developed regions. As one interviewee (F007) stated:

> *The benefits are very centered on people living around the nuclear power plants, which is why they don't want to see them closed. This is why people protest against closures, because they know that when you are living near a plant you have a music school,*

*swimming pool, and money for sports clubs, and it's very linked to the daily life of people.*

These areas received higher investment and better facilities, as well as being the source of hundreds of direct jobs (benefit 11).

Similarly, in Germany, solar PV has also benefited rural development in areas that otherwise may have suffered a lack of investment or under-population. As G001 highlighted:

*If you'd come 8 years ago, we would have discussed how the Germans are fleeing the countryside and moving into the city. Depopulation of the countryside was a big theme 10 years ago to 7 years ago. That stopped in part because of the renewable energy industry. And it's not just solar, it's also the biomass, it's also the wind. They're all activities that take place in the countryside, not in the cities.*

Solar PV was also connected with broader industrial development, with G001 noting a (temporarily) thriving "*solar panel manufacturing infrastructure*" that benefitted "*designers, developers, and innovators*." G002 commented on how German solar energy benefitted not only those "*who build PV panels on their roofs, but also an industry especially in the new Bundesländer, the Eastern part of Germany. So, it was also kind of industrial policy and structural support policy for these areas*."

In Norway, the benefits from EVs accrue to actors beyond merely the users of EVs themselves. N014 emphasized how Norwegian policy has spurred innovation for companies such as Tesla, as well as companies offering services related to charging infrastructure. N012 commented on how electricity suppliers benefit hugely from EVs as they can now provide fuel to large numbers of new customers.

In Great Britain, smart meters were associated with stimulating a host of new digital innovations across entirely new business models. GB007 stated that "*there is an almost infinite potential for new energy services or business models to emerge, to build on the infrastructure of smart meters, and to use data-driven services to help people*." GB010 added that "*we're going to see energy bundled up in a range of other services that will bring new opportunities for profit, and people will look to effectively create value out of the data streams that come in there*."

### *4.5 Incumbency: Disruption and democracy*

A final way of thinking about the co-benefits of low carbon innovation is the degree to which they disrupt patterns of socio-technical and political-economic incumbency (Johnstone and Kivimaa 2018). Importantly, this disruption may be specifically enabled by the fact that many of the innovations are user-based; demand more direct involvement and participation in energy decision-making; and allow individuals, households, or businesses to circumnavigate large, centralized incumbents (Schot et al. 2016). For this reason, some have claimed that these dynamics may potentially stimulate a greater degree of energy citizenship, participation, and ultimately democracy (Lockwood et al. 2013; Burke et al. 2017).

In terms of the four cases examined in this article, it could be argued that all four innovations have, in different ways, had this disruptive influence over the prevailing energy system, undermining pre-existing modalities and making new ones more viable or attractive. In France, although nuclear power is clearly itself a centralized form of energy that has been famously associated with France's centralized style of governance, it was undoubtedly disruptive in eroding the power of coal unions within the country and facilitating a shift away from the polluting coal industry – which improved air quality for many regions of France (Solomon & Krishna 2011). Moreover, the fact that nuclear is such a polarizing technology has also paradoxically been responsible for mobilizing and stimulating environmental awareness within France, as well as in actually improving the operation of the nuclear industry by forcing it to adopt higher standards. As F013 conceded: "*I think the industry has done a good job on safety, maybe because there was pressure from anti-nuclear groups!*"

In the other three cases, the more direct user-interface nature of the innovations makes them inherently amenable to more decentralized technical operation, and, as such, opens up opportunities for a greater degree of user participation and decentralized energy generation and governance. In the German solar case, for example, not only has the transition enabled a reduction in coal use, but it has also engendered a high degree of citizen participation in energy debates and has facilitated greater involvement in renewables and decentralized generation. As G006 argues:

> *You could talk about other values beyond financial things. What we still have in the Germany society is green thinking, so besides money people look at autonomy. Buildings are not autonomous… they decrease the share of dependence from the grid and from the utility. So that's also a participation in energy production and generation. So, citizens participate in an infrastructure that was previously dominated by very few large companies. That's also kind of a benefit.*

Similarly, in Norway, there is an argument that EVs have stimulated energy and climate change awareness and facilitated participation in energy transitions among constituencies who would not traditionally have been associated with such movements. As N014 stated:

> *What you can see from the statistics and the qualitative interviews we have done with users, many say that they have become more interested and more aware in energy consumption as a whole. So, they are taking this EV practice and the things they learnt through the engagement of this technology to other domains, for instance energy use in the house. There is a positive kind of rebound effect that most people talk about.*

Although many of the disruptive democratic benefits in the UK are more hypothetical due to the incipient nature of the smart meter roll-out, most interviewees recognized that smart meters have huge potential to stimulate new business models and decentralized and distributed energy generation – trends that are likely to lead to greater user engagement and a reduction in centralized incumbent power. As GB012 argued:

> *The thing that is important about smart meters is that they are a building block for new services and new ways of operating the system that are necessary, that allow customers to become active without them necessarily having to do anything about it, and then maybe get cheaper electricity or something like that. And honestly, if we don't operate the system more effectively then we can't have renewables, and so, it's one of these essential building blocks*

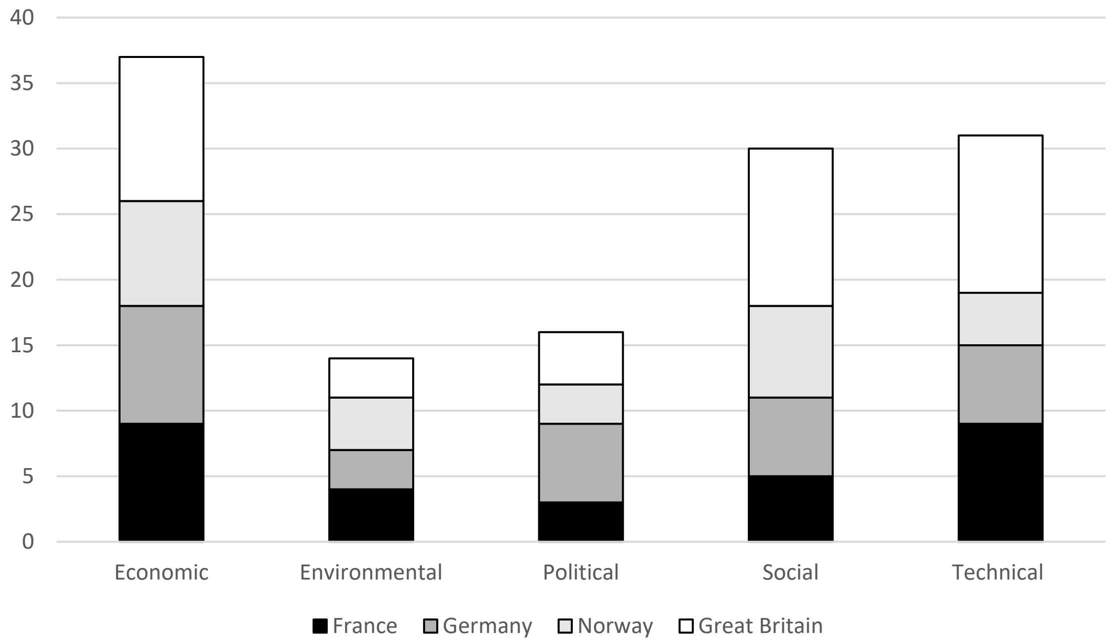
GB012 also stressed however that these benefits were dependent on the correct regulatory reforms being made that would take advantage of the new technical opportunities to bring this new system into being.

## 5. Conclusion and Implications

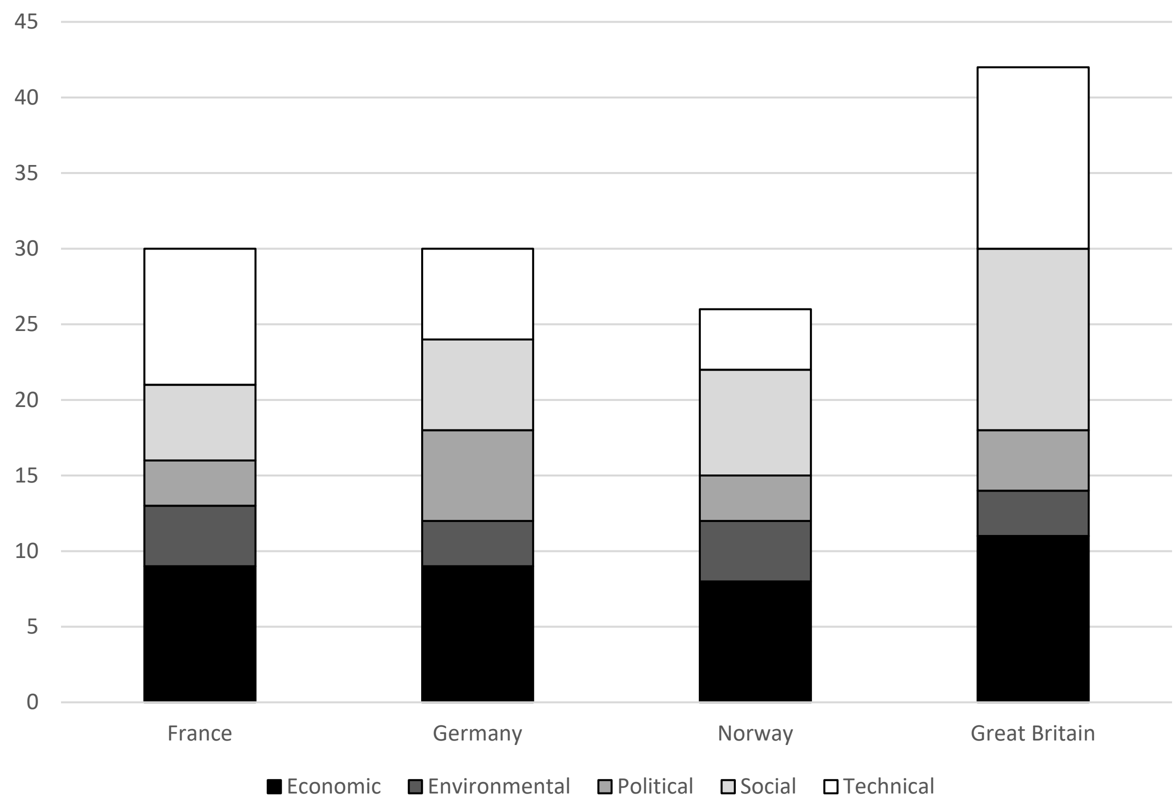
On aggregate, our interviews, focus groups, and internet forums across France, Germany, Norway and Great Britain resulted in an inventory of 128 presumed co-benefits to four low carbon transitions. As Figure 7 summarizes, a significant number of these were economic (37), such as fuel savings, jobs, exports, and profits. Others were environmental (14), such as displaced air pollution, mitigated climate change, reduced land use impacts, and other avoided externalities. But apart from these, our remaining 77 co-benefits do not fall into these broad categories of "cost" and "carbon." We captured 30 social benefits, as diverse as the way in which nuclear power galvanized national pride in France to the way in which electric vehicles elicited positive feelings of prestige and environmental consciousness in Norway. We captured 31 technical benefits, from the ways in which smart meters are facilitating distributed generation in Great Britain to the ways in which PV stimulated innovations in solar PV technology in Germany. We captured 16 political benefits, from policy learning across all four cases, as well as improvements to energy security and reduced energy dependence in all four cases. As Figure 7 also illustrates, when the data is transposed by country, Great Britain had the most potential co-benefits identified (42) followed by France (30) and Germany (30) with Norway (26) at the bottom. With this in mind, we offer three conclusions.

Figure 7: Summary of the 128 co-benefits to low carbon transitions by dimension and country

a. *Top panel: by co-benefit*




b. *Bottom panel: by country*




Source: Authors

First, for the energy studies and energy economics communities, we may need more sophisticated modeling, policy analysis, and even research designs that are capable of understanding and capturing the non-environmental and non-economic aspects of low carbon innovation. This holds especially true for social and political co-benefits, such as national pride (France), energy democracy (Germany), greater environmental consciousness (Norway), or feelings of comfort and convenience (Great Britain). Capturing these profuse, and at times obscure, co-benefits is especially important for the more difficult-to-predict (or quantify) dimensions, such as those relating to social and political processes. This finding becomes even more salient when such co-benefits have varying temporal timeframes, spatial scales, actors, and effects on incumbency and democracy. As such, we confirm the findings arising from Ürge-Vorsatz et al. (2014) and Bhardwaj et al. (2019), that the analysis of co-benefits, or energy and climate policy, demands a multiple-objective and multiple-impact framework.

Secondly, the complementarity and interoperability of innovations implies that transitions may gain momentum when multiple innovations are linked together in ways that improve their functionality or their ability to reconfigure entire systems. The implication here is that future low carbon transitions may require complementary innovations across an array of technologies, including those examined here, but also others, including:

- energy storage (e.g. batteries, flywheels, compressed air, pumped hydro);
- smart grids (to enhance flexibility and grid management);
- demand response (combining new tariffs and smart meters);
- network expansion (to increase capacity, connect remote renewables and link to neighboring systems) and to enable peer-to-peer trading; and
- new business models and market arrangements (such as capacity markets to ensure back-up generation).

Such complementarity of innovations suggests the need to move beyond analyzing individual technologies to entire systems. Indeed, it is not possible to fully distinguish the national versus technology differences across our four case studies because we only analyzed one technology per country, rather than the same technology across all four countries, or all four technologies across all four countries.

Thirdly, looking across these four transitions as a whole, our results pose methodological questions for low carbon energy transition research generally. Our findings, even though they are qualitative in nature, indicate that simple research designs (or policy mixes) that typically center on examining relationships between dependent and independent variables in order to develop generalizable laws may be inadequate in capturing the empirical complexity and multidimensionality of the transitions themselves. Certainly, rather than attempting to narrowly identify an omniscient causal relationship in any of our transitions that could yield the types of co-benefits we identify, our findings suggest that it may be more fruitful to search rather for *combinations* of multiple causal mechanisms and *conjunctions* between event chains (Ragin 2008). Analysts and policymakers should therefore aim to look beyond carbon pricing, and exclusively economic or environmental benefits, instruments, and institutions. Instead, they must recognize—and perhaps even celebrate—that low carbon transitions are ultimately processes that are as entangled in social affairs, political events, and technical innovation dynamics as they are in environmental and economic domains.

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## 7. Appendix I: Research design data tables

### Table A1: Semi-structured expert research interviews

| Country | Respondent number | Stakeholder type |
|---|---|---|
| *France* | F001 | Academia |
| | F002 | Academia |
| | F003 | Non-profit/civil society |
| | F004 | Think tank |
| | F005 | Industry |
| | F006 | Industry |
| | F007 | Government/regulator |
| | F008 | Think tank |
| | F009 | Think tank |
| | F010 | Non-profit/civil society |
| | F011 | Academia |
| | F012 | Non-profit/civil society |
| | F013 | Industry |
| | F014 | Academia |
| | F015 | Think tank |
| | F016 | Non-profit/civil society |
| *Germany* | G001 | Non-profit/civil society |
| | G002 | Industry |
| | G003 | Industry |
| | G004 | Government/regulator |
| | G005 | Non-profit/civil society |
| | G006 | Academia |
| | G007 | Government/regulator |
| | G008 | Non-profit/civil society |
| | G009 | Non-profit/civil society |
| | G010 | Industry - Trade body |
| | G011 | Consultant |
| | G012 | Industry |
| | G013 | Non-profit/civil society |
| | G014 | Academia |
| | G015 | Government/regulator |
| | G016 | Non-profit/civil society |
| *Norway* | N001 | Academia |
| | N002 | Industry |
| | N003 | Industry |
| | N004 | Industry |
| | N005 | Academia |
| | N006 | Industry |
| | N007 | Non-profit/civil society |
| | N008 | Non-profit/civil society |
| | N009 | Non-profit/civil society |
| | N010 | Government/regulator |
| | N011 | Non-profit/civil society |
| | N012 | Industry |

| | | |
|---|---|---|
| | N013 | Government/regulator |
| | N014 | Academia |
| | N015 | Industry |
| | N016 | Industry |
| *Great Britain* | GB001 | Academia |
| | GB002 | Government/regulator |
| | GB003 | Industry |
| | GB004 | Non-profit/civil society |
| | GB005 | Non-profit/civil society |
| | GB006 | Non-profit/civil society |
| | GB007 | Academia |
| | GB008 | Non-profit/civil society |
| | GB009 | Non-profit/civil society |
| | GB010 | Academia |
| | GB011 | Academia |
| | GB012 | Academia |
| | GB013 | Non-profit/civil society |
| | GB014 | Government/regulator |
| | GB015 | Industry |
| | GB016 | Industry |

Source: Authors

## Table A2: Public focus groups

| Country | Location | Participants |
|---|---|---|
| GB | Lewes | 2 |
| France | Colmar | 3 |
| Germany | Freiburg | 4* |
| Norway | Stavanger | 6 |

* Across two focus groups. Source: Authors

## Table A3: Public internet forum discussions

| Country case study | Forum | Description | Members | Responses |
|---|---|---|---|---|
| Norway | Elbilforum.no | Norwegian EV forum | 20,487 | 7 |
| Norway | Tesla motors club Norway | Online forum for Tesla owners in Norway | N/A | 4 |
| Norway | SpeakEV | Online electric car forum for all EV owners and enthusiasts | 16,152 | 0 |
| Germany | Photovoltaik forum.com | A solar forum in German | 100,823 | 2 |
| Germany | Solarstrom-forum.de | Photovoltaic forum in German | 2,329 | 0 |
| Germany | Building Technology Forum - Solar Energy | Online forum for all building technologies including solar | N/A | 0 |
| GB | Money Saving Expert | Consumer forum | 1,778,314 | 1 |

| | | | | |
|---|---|---|---|---|
| GB | Navitron | Private company forum on a range of energy issues | 7139 | 0 |
| GB | OVO Energy | Private company forum on a range of energy issues | | 0 |
| GB | The IET | The Institution of Engineering and Technology | N/A | 38 |
| France | Que Choisir | Consumer forum | 130536 | 1 |
| France | Forum photovoltaique | Energy forum | 42596 | 5 |
| France | Droit Finances | Consumer finances forum | N/A | 0 |

Source: Authors